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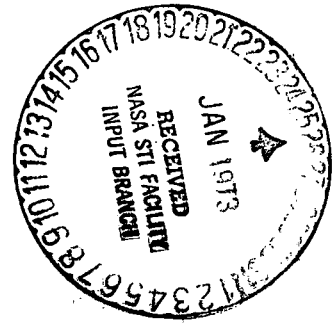

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16. Abstract

Conditions were experimentally studied for the onset of low-frequency oscillations and their fundamental characteristics in the oscillating electron ion source used in cyclotrons.

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Ion sources with electron oscillation and extraction of ion /818* flow across a magnetic field are widely employed as internal injectors in cyclic accelerators [1 - 3], which is determined by their high gas economy [4] and high efficiency in the formation of multicharge ions [5]. High stability of the charged particle beam at the accelerator output, which depends in particular on the stability of the ion flow extracted from the ion source [6], is required to solve a number of problems in experimental nuclear physics.

The specific properties of a discharge plasma with electron oscillation (a Penning discharge) determine the principal possibility of developing various "drift" type instabilities in it, which occur when low-frequency oscillations develop in the plasma [7, 8]. Based on our previous experimental investigations of low-frequency oscillations in a Penning discharge with a hot cathode [9, 10], we assumed that similar oscillations may develop in real ion sources and should have a considerable effect on the operation of such sources, leading in particular to considerable modulation of the ion flow, extracted across the magnetic field [9]. It should be noted that all data in [9, 10] were obtained at magnetic field intensities up to 1 kilooersted, whereas the magnetic field in the ion sources of cyclotrons are more than an

*Numbers in the margin indicate pagination in the original foreign text.

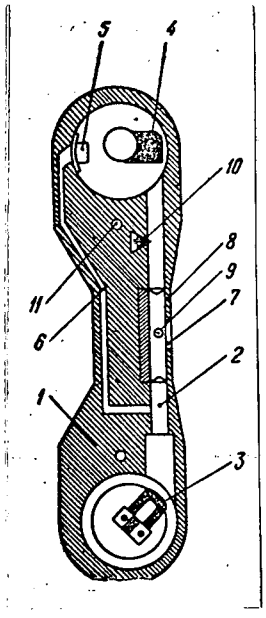

Figure 1. Diagram of ion source.

order of magnitude higher. Therefore, experimental verification of these assumptions in a real ion source was both of purely scientific and of practical interest.

The experiments were carried out in the ion source of the U-120 cyclotron of the Institute for Nuclear Research of the Academy of Sciences of the Ukrainian SSR, shown schematically in Figure 1. The main units of the source are a copper water-cooled anode block 1 with a discharge canal 2 having a diameter of 5 mm, a U-shaped directly heated tungsten cathode 3 with a diameter of 1.5 mm, and a cooled tungsten reflector 4 (11 is the water cooling channel). The distance between the cathode and reflector is 95 mm. The working gas is fed into the discharge channel through the gas supply pipe 5 and the gas feed channel 6. The ion beam is extracted through slot 7 measuring 2 x 8 mm in detachable plate 8. Three fixed probes were introduced into the anode channel to investigate the discharge plasma. Two of them (one probe 9 is shown in Figure 1) were positioned in the metal cavity of the anode with an azimuthal shift of +90 and -90° with respect to the source output slit. The third probe 10 was shifted along the length of the channel toward the reflector and rotated 180° in azimuth with respect to the source output slit. A uniform magnetic field, directed from the cathode to the reflector, is created by an electromagnetic cyclotron.

The discharge is accomplished in a stationary mode with a /819
discharge current of I_a = 1 - 2 A and a voltage drop at the discharge of V_a = 100 - 200 V; the reflector and cathode are

positioned with respect to the grounded anode for an identical potential. The ion beam is extracted by a high-frequency voltage (f = 10.92 MHz, U = 80 kV) on the D-electrodes of the cyclotron. The beam extracted from the cyclotron is recorded by a high-speed scintillation detector, connected either to an oscillograph or to a frequency analyzer.

The main source of information on the plasma behavior in the discharge chamber was the electronic current in the probe circuit connected through a low-value resistor (R = 1 - 5 ohms) to the anode. A V6-6 selective microvoltmeter and a S4-8 frequency analyzer were used to analyze the frequency spectrum of oscillations in the discharge plasma and in the beam extracted from the cyclotron in the range of 1 kHz to 30 MHz. The shape of the oscillations, phase shifts, and modulation factor were determined by the oscillograph probe current and beam current with the aid of S1-16, S1-29 and S1-8 oscillographs.

To solve the problem, it was first necessary to determine whether low-frequency oscillations occur in the discharge at a magnetic field intensity of 1 - 20 kilooersteds. For this purpose, the range of current variation in the probe circuit at different magnetic field intensities was investigated with the high-frequency voltage on the D-electrodes switched off. The experiment showed that intensive oscillations having a frequency ranging from hundreds of kilohertz with a typical spectrum in the form of a number of narrow peaks, corresponding to the main frequency and its harmonics (10 harmonics each were observed in a number of cases), occur in the plasma when the magnetic field intensity exceeds several kilooersteds. The frequency of these oscillations depends on the magnetic field intensity, gas flow rate, and discharge voltage. The dependence of frequency on discharge current is very weak. The connection of the reflector to the anode (a direct arc discharge) leads to almost complete disappearance of the indicated oscillations.

Comparison of the phases of current fluctuations in the probe circuit showed that, as in [9], the plasma contains a density wave, running along the azimuth in the direction of plasma rotation in the crossed electric and magnetic fields in the presence of /820
radial deflection of the potential. The modulation factor of the probe current was close to 100%. Depending on the magnetic field intensity, oscillations were observed with an azimuthal mode of m = 1, 2, and 3, and in some cases with m > 3.

It was of interest to determine the critical magnetic fields for the development of each oscillation mode, and their dependence on the gas flow rate. Such experimental relations, obtained with a discharge in deuterium, helium and neon, are presented in Figure 2. The pressure in the discharge, calculated according to the gas flow rate Q (cm^3/min), comprised $p \approx 1.6 \cdot 10^{-3} \cdot Q$ mm Hg for helium and deuterium and $p \approx 3.6 \cdot 10^{-3} \cdot Q$ mm Hg for neon. In the case of a discharge in deuterium, oscillations with the mode m = 3 were observed only simultaneously with those of mode m = 1; the region where these modes coexist is denoted by the letter a in Figure 2. Oscillations with an even mode of m > 2 were observed with a magnetic field intensity below the critical value for mode m = 2.

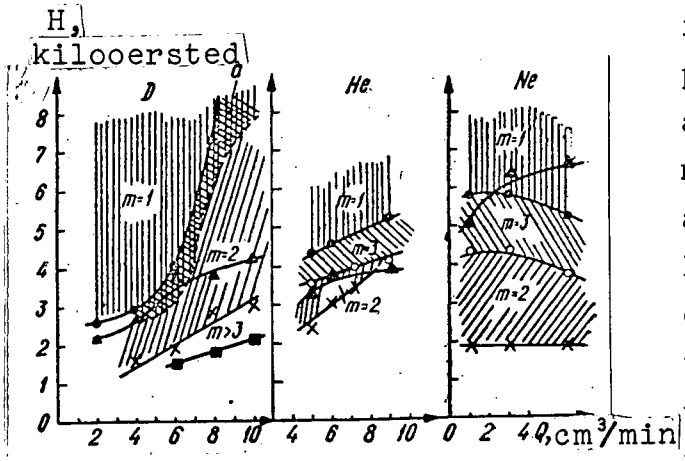

Figure 2. Dependence of critical magnetic excitation fields of modes m = 1, 2, 3 on gas flow rate. I_a = 1.2 - 1.7 A, V_a = 120 - 180 V and A was calculated by Formula (1).

The data presented in Figure 2 indicate primarily that the characteristic sequence in alternation of modes according to magnetic field, obtained in [9], occurs in the given case as well. The critical magnetic fields usually increase as the pressure in

the discharge increases. The slight decrease of the critical magnetic field observed in Figure 2 upon transition from mode m = 3 to m = 1 during discharge in neon correlates with the results presented in [9].

An investigation of low-frequency oscillations in a Penning discharge with a magnetic field intensity of up to 1 kilooersted [9] indicated that the dependence of the critical magnetic field, at which oscillations with mode m = 1 occur, on the discharge and system parameters is described satisfactorily by the empirical formula

$$H_{cr.1} = Ap^{1/3}V_a^{1/3}M^{1/2}d_a^{-1}I_a^{-0,1}, \quad (1)$$

where p is the gas pressure in the discharge, V_a is the voltage drop on the discharge, M is the atomic weight of the gas, d_a is anode diameter, I_a is the anode current, and A is a constant, calculated from experimental data.

It was of interest to compare the observed values of the critical magnetic fields of those calculated by (1). The results of the calculation for a discharge in deuterium, helium and neon are shown in Figure 2. We can see that, in the case of discharge in deuterium with low flow rates of gas and discharges in helium and neon, the calculated values of $H_{cr.1}$ are in agreement with those obtained experimentally with an accuracy up to 1 kilooersted. It should be noted that under experimental conditions the magnetic fields were measured with an accuracy up to 0.5 kilooersted; the cathode geometry in the present experiments was not provided by strict axial symmetry of the plasma column. The value of A, calculated from data in [9], was used in the calculations. Taking

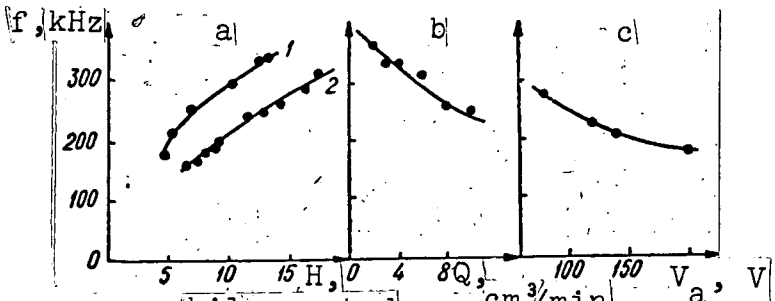

Figure 3. a — I_a = 1.3 A; V_a = 150 V; 1 — Q = 5 cm³/min, D_2; 2 — Q = 6 cm³/min, He; b — I_a = 1.5 A, V_a = 140 V, H = 10.5 kilooersteds, D_2; V — I_a = 1.5 A, Q = 5 cm³/min, H = 5.3 kilooersteds, D_2.

into account these circumstances, the observed agreement of experimental and calculated values of $H_{cr.1}$ is satisfactory, and indicates that the empirical dependence (1) obtained in [9] is also valid under the conditions of the present experiment. The rapid increase of the critical magnetic field observed experimentally in the case of a discharge in deuterium with high gas flow rates, not in agreement with Formula (1), is apparently determined by the specific type of gas. We previously observed a similar effect in a magnetic field up to 1 kilooersted with a discharge in hydrogen.

The dependence of the oscillation frequency with mode m = 1 on magnetic field intensity, gas flow rate and discharge voltage is presented in Figure 3. A comparison of these functions with /821 those previously obtained in [9] indicates that the nature of the frequency variation of oscillations as discharge parameters vary is identical in both cases. A calculation of similar functions for oscillations with modes m > 1 is difficult due to the narrowness of the zones where these modes exist and the impossibility of precisely regulating the magnetic field at low values.

It is noted in [9, 11, and 12] that the more probable cause of development of low-frequency oscilllations in a Penning discharge plasma with a hot cathode is the development of instability in it, related to rotation of the plasma in the crossed radial electric and axial magnetic fields. In this case, the azimuthal

phase velocity of the wave is determined by the azimuthal velocity of plasma drift in the crossed fields, under conditions of the present experiment it is similar to it [13]. The radial electric field, calculated from experimental data, is approximately 50 V/cm, and the corresponding radial potential deflection is 10 V, which is quite realistic.

Besides the above-described oscillations in magnetic fields greater than 10 kilooersteds, oscillations with a frequency in the range of 2 - 3 MHz were observed in a discharge in deuterium. These osciallations are characterized by a wide range ($\Delta f \approx 1$ MHz) and intensity, which is approximately an order of magnitude less than the intensity of the first harmonic of azimuthal oscillations with mode $m = 1$. The frequency of these oscillations did not depend on the gas flow rate, magnetic field intensity, or discharge current and decreased very slightly as the discharge voltage increased. The amplitude of the oscillations increased as the gas flow rate and voltage drop on the discharge decreased, and as the discharge current increased. An investigation of the nature of these oscillations was not the purpose of this investigation and is of independent interest.

An important experimental fact obtained in the present investigations is that, for a cyclotron with working magnetic field intensity and gas flow rate, there are intense and clearly expressed oscillations in a discharge with an azimuthal mode of $m = 1$, resulting in almost 100% modulation of the plasma density near the source anode,and consequently, in the region of the output slit as well. The latter should have a considerable effect on the stability of the charged particle beam extracted from the discharge and accelerated in the cyclotron. In connection with this, the oscillations in the deuteron beam extracted from the cyclotron and those in the ion source plasma were compared experimentally.

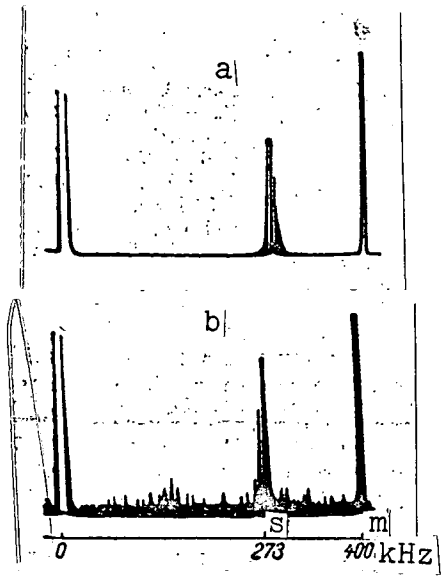

Figure 4. I_a = 1.2 A, V_a = 150 V, Q = cm^3/min, H = 14.5 kilooersteds (s is the signal and m is the marker).

The experiments indicated that all the oscillations observed in the source appear in the frequency range of the beam; the dominant (in amplitude) harmonic is the first harmonic of oscillations with mode m = 1. The region of the spectrum with this harmonic, registered by the probe in the source (a), and corresponding to the region of the spectrum of oscillations in the beam extracted from the cyclotron (b), is presented in Figure 4. It is obvious that the spectra are completely identical. /822

The form and degree of ion beam modulation at the cyclotron output may be judged from the experimental data presented in Figure 5. Oscillogram, a, of Figure 5 corresponds to the electron current in the circuit of the probe source I_p inserted into the plasma, recorded by an S1-29 oscillograph with an open input with a single scanning lasting 1 microsecond/division. One may see that modulation of the probe current by low-frequency oscillations is almost 100%. Oscillations of ion beam current I_b at the cyclotron output, registered by an S1-29 oscillograph with single scanning of the same duration are shown in

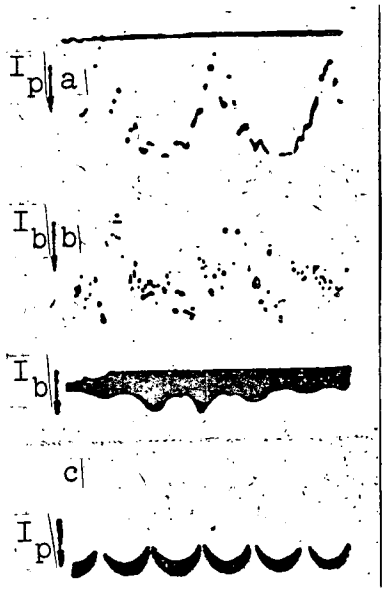

Figure 5. I_a = 1.2 A, V_a = 150 V, Q = 5 cm^3/min, H = 14.5 kilooersteds.

oscillogram b of Figure 5. Since the ion beam is extracted from the discharge plasma by a variable voltage with frequency f = 10.92 MHz, as we can see, the ion beam at the cyclotron output represents pulses following at a frequency f = 10.92 MHz (the points on the oscillogram), whose amplitude is deeply modulated by the frequency of oscillations in the discharge. The oscillograms of oscillations in the probe circuit, intersected at 180° in azimuth with respect to the output slit of the source (the lower beam), and those of oscillations of the beam current at the cyclotron output (upper beam), obtained on a S1-16 double-beam oscillograph for a scanning of 2 microseconds/division, are presented in Figure 5c. It is easy to see that the minimum current in the probe circuit corresponding to the maximum plasma density in the region of the output slit of the source correlates with maximum beam current at the cyclotron output. In this case, the degree of beam modulation by low-frequency oscillations, estimated from an analysis of a number of oscillograms, comprises not less than 60 - 70%. Some decrease in the degree of beam current modulation compared to current modulation in the circuit of the probe, located on the periphery of the source plasma, may be explained by assuming that the plasma boundary is located inside the discharge chamber, and the extent of density modulation of the plasma by oscillations, as indicated in [9, 10], decreases toward the discharge axis.

The results of an analysis of the experimental data outlined /823 in this investigation lead to the following.

1. The investigated low-frequency oscillations in an ion source with electron oscillations in a strong magnetic field and the oscillations, described previously in [9, 10], in a discharge with electron oscillations in weak magnetic fields are determined by the development of identical instability in the plasma. This

is confirmed by the conformity of the main characteristics of the oscillations, namely: the direction of motion of azimuthal density waves, the specific frequency range of oscillations, the sequence of alternation of oscillation modes according to the magnetic field, the dependence of critical magnetic fields and oscillation frequency on discharge parameters.

2. The empirical formula derived in [9], and reflecting the dependence of the critical magnetic field for the development of oscillations with azimuthal mode m = 1 on discharge parameters and the system, satisfactorily describes the behavior of a discharge in a strong magnetic field, and thus may be used for an approximate calculation of the critical magnetic field over a wide range of discharge conditions. (An exception is the region of high pressures in a discharge in deuterium.)

3. The oscillations with azimuthal mode m = 1, occurring in the ion source plasma of a cyclotron, have a considerable effect on the operation of the ion source, determining as a result the considerable modulation of the beam extracted from the cyclotron.

In connection with this, it is necessary to stabilize the low-frequency instability which develops in an ion source with electron oscillation. Of the methods of stabilizing "drift" type instabilities, proposed up to the present [14 - 17], the simplest and easiest to accomplish under conditions of an internal ion injector is apparently either a considerable decrease in the diameter of the anode discharge channel or the introduction of grids into the channel, which are divided into a number of channels of smaller cross-section [17]. By the proper selection of the channel or grid cell dimensions, a critical magnetic field for oscillations with mode m = 1, which exceeds the working

magnetic fields of the cyclotron, may be achieved according to Formula (1).

In conclusion, the authors express their deep gratitude to G. A. Kosinov for discussing the problem and results of the present investigation, as well as for the apparatus willingly made available for recording the cyclotron-accelerated beam and the opportunity of making the measurements, Ye. M. Bel'skiy for the ion source design modification required to carry out the experiments, and to Yu. S. Produvalov for assistance in conducting the experiment.

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